More and more NanoLinks

Juergen Brugger
Ecole polytechnique fédérale de Lausanne, Switzerland

More and more NanoLinks *

Nanolink*

- Links between micro and nanoscale (e.g. an AFM tip)
- Knowledge Links to bridge top-down with bottom-up nano-manufacturing
- Interdisciplinary research activities bridging Microengineering and (supra)molecular engineering pioneered by UTwente (~1998) with the NanoLink strategic research orientation

MESA+
The Top-Down meets Bottom-Up vision

H. Rohrer (1992)
IBM Zurich Research

Let us look back in time
e.g. 30 years ago
Over the years we
• Gained new knowledge from nanoscience
• Built tools for imaging, fab and simulation
• Developed methods for rapid prototyping

STM: 10 years after, Ultramicroscopy 42-44 (1992)
The nanoworld: Changes and challenges, Microelectronic Engineering 32 (1996) 5-14

Size of tools to interact with nanometer scale

Charged particles
Near-field interactions

light
2 NanoLink examples that have made tremendous progress over the last 30 years and form the basis for future nanomanufacturing:

1. AFM as writer tool (top-down, rapid prototyping)
2. Capillary assisted templated self-assembly (bottom-up, high-volume)

The Atomic Force Microscope as NanoLink

- AFM probe tip
- 1000 times smaller than a record player needle
- Micromachined Silicon AFM cantilever
Scanning Probe Microscopy in the ‘80/’90s and today

DNA double helix imaged by AFM

Anno 1999 (bio-physics)  Anno 2014 (biology)
Lithography in the ‘80/’90s

Optical lithography in 1989

Optical Projection Lithography Using Lenses with Numerical Apertures Greater Than Unity

Hiroaki Kawata\textsuperscript{X}, James M. Carter\textsuperscript{XX}, Anthony Yen\textsuperscript{XX} and Henry I. Smith\textsuperscript{XX},

\begin{itemize}
\item University of Osaka Prefecture, Japan, \textsuperscript{X}Department of Electrical Engineering and Computer Science, M.I.T., Cambridge, Mass.02139, U.S.A.
\end{itemize}

\begin{figure}
\centering
\includegraphics[width=0.3\textwidth]{figure7}
\caption{Pair of metal lines obtained by optical projection lithography and the process depicted in Fig. 7, with $\lambda = 433$ nm and $\text{NA} = 1.4$. Metalization is 10 nm Cr, 100 nm Au. Metal lines are about 20 \textmu m wider than original resist images.}
\end{figure}
Scanning Probe Lithography in the ‘80/’90s and today

A 900 nm by 900 nm AFM image of the constriction and oxide junction (circle). Vertical colour scale bar ranges 4 nm from black to white.
**Thermal Scanning Probe Lithography as potential game changer**

*No charged particles
- No or less damage to fragile material systems
- "Just" heat

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**Early attempts in t-SPL**

- Explosive PETN: low patterning temp.
- Polycarbonates: \textit{thermal flow} \Rightarrow increase cross-linking

*Images and references:
Early attempts in t-SPL

Diels Alder polymer

Molecular Glass

PPA


D. Pires, Science 2010

Knoll, Adv. Mat., 2010

Coulombier, Macrom., 2010

Resist evaporates

High speed t-SPL
or how to match throughput of electron beam lithography

Physical limitations

- Reaction kinetics: sufficient “heat dose” from the tip for resist decomposition
- Vertical movement of cantilever is limited by force for up & down
- Lateral scan speed is limited by piezo stages and trade-off with positioning accuracy

Record results

- 1 us contact time of the hot tip sufficient for PPA resist (hence ≈ 1000 x faster than other Scanning Probe Litho)
- 500 kHz pixel rate (controlled vertical movement up + down)
- 20 mm/s scan speed (as fast as high resolution Electron Beam Lithography)

No need for development steps

Paul et al., Nanotech. (2011)
**High resolution**

*Demonstrated in Si:*

- Feature size
  - Record 7 nm
- Feature density
  - < 15 nm half-pitch lines and spaces
- Line edge roughness
  - < 3 nm (3σ)

**Process flow:**

- T-SPL in 10 nm thin PPA resist
- Reactive ion etching using a hard mask stack

9 nm trench with 2.3 nm LER (3σ)

„Nested-L“ structure with 13.8 nm half-pitch

Wolf et al., JVSTB, (2015)
Unique applications for t-SPL

Direct patterning of functional material systems that are heat sensitive. Fast heating/cooling rates @ 10nm scale.

1. Silk film as water soluble resist
2. Fluorescent supramolecular polymer

Silk fibroin as a resist for thermal scanning probe lithography

Natural biomaterial
Interesting properties for biomedical microsystems

Samuel Zimmermann, MNE 2017 – Braga, paper in prep.
Silk fibroin

- Good mechanical (E = 1-8 GPa) and optical properties (T > 90%)
- Protein extracted from natural silk
- Chemical and biological functionalization
- Polymorphic secondary structure

Silk fibroin extracted from bombyx mori cocoons
- Spin-coating 4% solution (4000 RPM) → ~150 nm thin film
- Soft-baking at 90 °C to remove residual water
- Annealing by immersion in EtOH, MeOH or water steam
- Local heating with a t-SPL probe (400-500 °C for 8 µs)
- Development in water (10 sec)
**Patterning Mechanism in silk**

- Short heat pulses (8 μs)
- Fast heating, cooling rates (>10³ K/s)
- Change water solubility

**Resolution in silk**

- 50 nm half pitch size (30 nm deep)
- 110 nm half pitch size (100 nm deep)
- RMS unpatterned: 1.6 nm
- RMS patterned: 2.5 nm
Unique applications for t-SPL

Direct patterning of functional material systems that are heat sensitive. Fast heating/cooling rates @ 10nm scale.

1. Silk film as water soluble resist
2. Fluorescent supramolecular polymer

T-SPL in supramolecular fluorescent polymer film

With Adolphe Merkle Institute Fribourg, Switzerland

S. Zimmermann, D. Balkenende, et al. (ACS Applied Materials & Interfaces)
T-SPL in supramolecular fluorescent polymer film

S. Zimmermann, D. Balkenende, et al. (ACS Applied Materials & Interfaces)

In this talk 2 NanoLink examples that have made tremendous progress over the last 30 years and form the basis for future nanomanufacturing:

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2. Capillary assisted templated self-assembly (bottom-up, high-volume)
Capillary assembly of nanoparticles

Challenges to control

- Position
- Orientation
- Interparticle gap
- Yield on larger area

Natural assembly by Drop casting

Still et al., Langmuir 2012
From suspension to substrate
**Liquid blade coating**

- motorized translation stage
- Peltier element
- colloidal suspension
- topographical template

*From suspension to substrate*

**Top view**

- blade (fixed)
- meniscus
- 25 µm

**Blade coating**

*From suspension to substrate to traps*

Mastrangeli, Adv. Mater. 2015
**Blade coating: prior art**

Never really ‘perfect’

One key is the **trap**
e-beam litho, etching, surface functionalization

The other key is **process control**
during assembly
Temp, humidity, speed, colloidal suspension
Typical assembly using ordinary straight-edged traps

Improved assembly using funneled traps (angle control)
Even better assembly yield using trap with funnel and auxiliary fin

Nanogap tuning in nanorod dimers

V. Flauraud et al., Nat. Nanotechnol. 2017
A tool for arbitrary designs

V. Flauraud et al., Nat. Nanotechnol. 2017

3D orientation of Ag nanocubes

V. Flauraud et al., Nat. Nanotechnol. 2017
The Top-Down really meets the Bottom-Up

- Scientific curiosity has driven a need for new tools for imaging.
- It enabled new methods for fab
- New computer power improved simulation
- Now we have a rapid turn-around prototyping
- Pathways for high volume
- Nanolinks enable better devices and systems and finally enable new applications
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Ecole polytechnique fédérale de Lausanne
THANK YOU.